NAMI-955

RADIATION MONITORING WITH NUCLEAR EMULSIONS ON PROJECT GEMINI

I. EXPERIMENTAL DESIGN AND EVALUATION PROCEDURES. PARTIAL RESULTS ON MISSIONS 4 AND 5

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JOINT REPORT

UNITED STATES NAVAL AEROSPACE MEDICAL INSTITUTE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

February 1966

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RADIATION MONITORING WITH NUCLEAR EMULSIONS ON PROJECT GEMINI

1. EXPERIMENTAL DESIGN AND EVALUATION PROCEDURES: PARTIAL RESULTS ON MISSIONS 4 AND 5*

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Bureau of Medicine and Surgery
MFO 22.03.02-5001.33

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18 February 1966

*This work was conducted under contract with the Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas.

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PENSACOLA, FLORIDA

SUMMARY PAGE

THE PROBLEM

Small packs of nuclear and ordinary film badge emulsions, combined with thermoluminescent and other radiation sensors to compact pliable units, were worn by both astronauts on Gemini missions 4 and 5 in the helmet, on left and right sternum, and in the thigh pocket. Previous measurements with emulsions on Mercury missions 8 and 9 had shown that a large part of the total ionization dosage was due to exposure to trapped protons in the South Atlantic Anomaly. A quantitative analysis of the energy spectrum of these protons required a sustained resolution for protons of several hundred down to zero Mev. This objective was accomplished by the use of pairs of 200 micra Ilford G.5 and K.2 emulsions in the packs.

FINDINGS

The track populations in the processed emulsions were evaluated by microscopic track and grain counting of selected small areas in each emulsion sheet. The grain count/LET function was established separately for each set of emulsions and for each individual observer by means of proton and alpha enders. With the grain count/LET relationship known, grain count classes could be converted to LET and energy classes which in turn defined the integral and differential flux showing a well-defined, broad maximum in the 30 to 40 Mev energy interval. The pack in the command pilot's helmet on Gemini 4 recorded a proton dose of 48 millirads; the one on the command pilot's left chest on Gemini 5 showed a dose of 105 millirads.

No special efforts were made to analyze the directional distribution of the track segments in the scanned emulsion volumes. However, ratios of up to 1:1.6 for the enders counts of emulsion areas at opposite edges of the same sheet furnished proof of pronounced absorption effects in the emulsions, which was to be expected in view of the large differential flux at low energies.

The findings indicate that on Gemini orbits, the bulk of the total mission dose was due to trapped protons in the South Atlantic Anomaly. The large fraction of low energy particles in the trapped radiation creates marked differences in the flux at different locations within the vehicle due to local absorption effects. Such effects occur even in the radiation sensors themselves, causing marked variations in the readings at locations only millimeters apart.

ACKNOWLEDGMENTS

The authors wish to acknowledge the expert assistance of M. G. Basha, N. V. Hamlett, R. J. Mayberry, V. C. Yoder, J. C. Jastremski, and S. E. Burch in scanning the emulsions.

INTRODUCTION

Previous measurements with nuclear emulsions on Project Mercury space flights, especially on missions MA-8 and 9 (1, 2), had established the fact that by far the largest part of the ionization dosage within the vehicle was due to protons in the zero to 300 Mev energy band picked up in the South Atlantic Anomaly. The continued services of the U. S. Naval Aerospace Medical Institute were requested by the Manned Spacecraft Center of NASA to provide small nuclear emulsion packs for Project Gemini to be assembled with thermoluminescent and other radiation sensors, designed by MSC directly, into a compact unit. Whereas the latter sensors would furnish information, immediately after the mission, on the integral rad doses received, the nuclear emulsions would supplement that information by a detailed account of particle fluxes and energy spectra after completion of the tedious and time consuming evaluation by microscopic track and grain counting. In view of the time requirements involved in nuclear emulsion work, it seems desirable to report partial results as they become available in the progress of scanning. The following report is such an interim account. It describes the experimental design and the method of track evaluation and presents representative proton energy spectra obtained on Gemini 4 and 5.

EXPERIMENTAL DESIGN

Contrary to the Mercury measurements which were carried out with stationary emulsion packs fastened to consoles of the vehicle frame, radiation monitoring on the Gemini missions was to be accomplished by means of flat pliable packs to be worn by the astronauts within their space suits. As these packs were to accommodate, in addition to the nuclear emulsion sheets, the other sensors mentioned above, allowances of weight and size were severely reduced as compared to the Mercury packs.

As mentioned above, the bulk of the radiation exposure in orbit was to be expected from protons in the zero to 300 Mev energy interval. Even within this limited interval the differential dose contribution per Mev varies substantially, being largest at lowest energies and dropping slowly and continuously to an insignificant level at about 300 Mev. In view of this particular configuration of the spectrum, it was desirable to ensure sustained resolution of energy over the entire spectral region in question, with special emphasis on low energies down to zero Mev. Based on experiences gained in the Mercury measurements, it was decided to rely for this purpose on Ilford G.5 and K.2 pairs of 200 micra emulsions on Melinex. To be prepared for unexpected gross overexposure from nucleonic components, one Kodak NTA neutron monitoring film badge emulsion and, for overexposures from electrons, one Kodak Type 2 double component pair of film badge emulsions were added. The complete photodosimeter pack thus contained a total of 5 film sheets of 1 by 1.5 inches. As mentioned above, it was combined with other passive radiation sensors to a compact unit. Each astronaut carried four units on his body. They were located in the helmet, on right and left sternum, and in the thigh pocket. On mission Gemini 4, additional boxes containing nuclear emulsion sheets of 0.5 by 0.5 inch size, arranged in sets of three with emulsion planes at right angles to each other, were flown in aluminum containers accommodating a variety of additional passive sensors prepared by the Air Force Weapons Laboratory (3). The results obtained with these stationary sensors located in aluminum containers inside the vehicle will be reported separately at a later time.

DATA EVALUATION

The basic procedure of establishing, by microscopic track and grain counting, flux and energy spectrum of the proton exposure has been discussed in detail in an earlier report on the Mercury data (l.c., 1), hereafter referred to as Report 27. The G.5 and K.2 emulsions flown on Gemini 4 and 5 were evaluated essentially by the same method except for one important improvement. As pointed out in Report 27, the grain count in a fully developed G.5 emulsion becomes insensitive for energies below about 50 Mev due to grain saturation. As this energy lies in the region of maximum differential flux for the proton exposure in the South Atlantic Anomaly, the indicated shortcoming of the G.5 emulsion is very undesirable. As shown also in Report 27, this lack of spectral resolution can be remedied to a certain extent by means of the enders count, which reliably defines the flux at zero Mev thereby allowing the establishment of the low energy section of the spectrum by interpolation. Nevertheless, a method which would define the entire low energy region directly by grain counts would seem greatly preferable.

Figure 1 demonstrates how the just-specified sustained resolution over the full energy interval from zero to several hundred Mev can be accomplished by using a pair of G.5 and K.2 emulsions. As is seen from the upper graph in Figure 1, the K.2 emulsion has a substantially lower sensitivity than the G.5 in the sense that the grain count of a particle of given LET in K.2 emulsion is much lower than in G.5. As a consequence, the K.2 emulsion gives good resolution, i.e., sufficiently low grain counts for proton tracks of low energies which would appear heavily saturated in G.5 emulsion. For interpretation of the two senstivities shown in Figure 1 in terms of proton energy and residual track length in emulsion, Table I should be consulted in which the relationship between range, energy, and LET for emulsion is tabulated (4). A grain count of 160 grains/100 micra emulsion can still be resolved very satisfactorily. For K.2 emulsion, this corresponds to an LET of about 50 kev/micron emulsion and an energy of slightly less than 1.0 Mev. The price to be paid for this excellent resolution is the limitation of the K.2 emulsion to low energy protons. Under optimum conditions, i.e., for a very low level of background grains, an experienced observer can still identify the track of an 80 Mev proton, i.e., a track of about 25 grains/100 micra emulsion. The K.2 emulsions flown on the Gemini missions showed markedly higher background levels, limiting the maximum identifiable energy to 45 to 50 Mev. Since a 50 Mev proton produces, in G.5 emulsion, a track which still can be grain counted with satisfactory resolution, the limitation of the K.2 emulsion to energies below 50 Mev does not impair the accuracy of the measurements.

Table I

Range, Energy, and Linear Energy Transfer for Protons in Emulsion*

Kinetic Energy, Mev	Range, micra Em.	LET, Kev/micron Em.
0.80	10	55.8
2.30	50	28.8
3.54	100	21.7
5.40	200	16.3
9.33	500	11.1
14.0	1000	8.15
20.9	2000	5.98
35.1	5000	4.01
52.2	10,000	2.96

*Data of Barkas. See reference (4).

It should be pointed out that the lowest grain density for recognizing a straight track in any emulsion is not a sharply defined value. Since the background of scattered grains always shows variations from visual field to visual field, the minimum grain spacing for a straight track that can still be picked up in the scanning process varies from field to field. It also depends on the magnification used for scanning and on the skill and concentration of the observer. As a consequence, the efficiency of track identification in the K.2, which is 100 per cent from zero to about 45 Mev, drops gradually toward higher energies. However, the measurement of the flux is not influenced by this lack of a sharp limit in the track identification of the K.2, since the smooth contour of the overlapping flux/LET curves from the G.5 and K.2 track counts defines the true flux/LET function in the critical energy interval of change-over.

It is implicitly clear from the foregoing discussion that the accurate determination of the energy spectrum hinges on the grain count/LET function shown in Figure 1. This function cannot be generally established since it depends on a number of variable factors such as developing conditions and, with regard to the individual observer, on blob interpretation and rejection of pinpoint grains. Therefore, the grain count/LET relationship must be determined anew for each batch of films and for each observer individually. This is accomplished best by means of proton and alpha enders. Since the range/energy and LET/energy functions for protons and alpha particles in emulsion are well known, LET and energy at any point of a particle track ending in emulsion

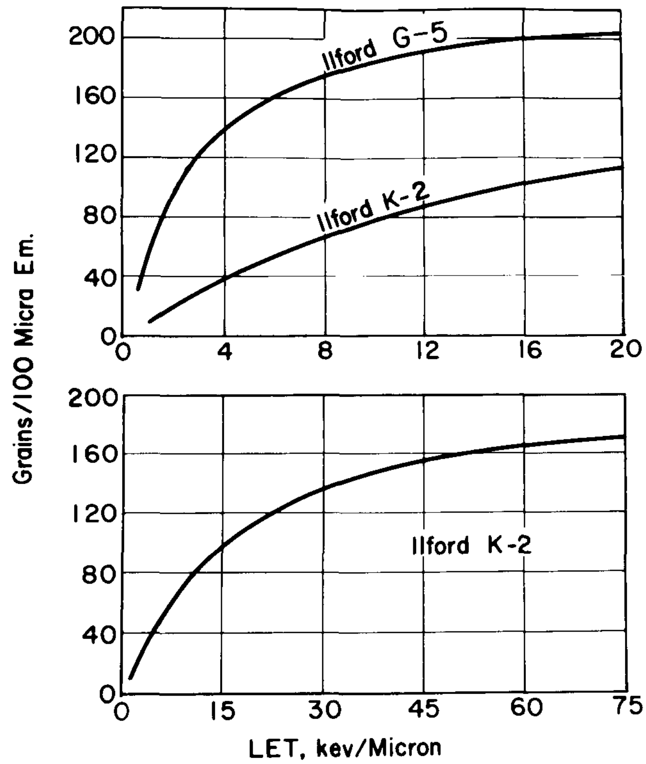

Figure 1

Typical Grain Count/LET Functions for Ilford G.5 and K.2 Emulsion

can be determined from the residual range. Because the bulk of the flux of trapped particles in the South Atlantic Anomaly consists of low energy protons, the G.5 and K.2 emulsions flown on the Gemini missions contain proton enders in larger numbers. Alpha enders are needed only for the grain count calibration of the K.2 emulsion. Since alpha particles are not a component of trapped radiation, single alpha enders are quite rare in the flown emulsion. It is therefore much more expeditious to select ending alpha prongs of large disintegration stars for the grain count calibration.

With regard to proton enders, it should be pointed out that a population of proton tracks from trapped radiation differs basically from a population obtained from exposure to primary galactic radiation. As Waddington (5) has pointed out, proton enders in an emulsion stack exposed to galactic radiation are exclusively of local origin produced as secondaries in nuclear interactions of high energy primaries with atomic nuclei of the emulsion material, mainly silver and bromine. Quite differently, enders in a proton population from trapped radiation are predominantly low energy primaries with disintegration stars contributing only about 10 per cent to the total enders count. It is no problem to determine this latter contribution separately and to correct the gross count accordingly.

Once the grain count/LET function is established, the raw scores of the scanning procedure furnishing number, individual length, and grain count of all track segments in a given emulsion volume can be expressed in terms of differential flux by converting grain count classes to LET and finally to energy classes. A special problem concerns the most suitable way of denoting flux in the final presentation of the results. Recording the directions of incidence in a 200 micro emulsion layer is not possible since almost all track segments are through-shots ending outside the emulsion. For assessments of rad dose, the directional distribution of the particles in the scanned volume is irrelevant anyway since dose depends only on total track length and LET per unit volume. Computationally, the total track length per unit volume is obtained by dividing the total length recorded in a scanned volume by that volume. Hence, its dimension is cm/cm^3 or cm^{-2}. The ordinate units Protons/cm^2 and Protons/cm^2 Mev in Figures 2 to 4 should be understood in these terms. In other words, they do not represent actual flux values, but merely equivalent unidirectional flux values which would furnish the same total track length in a given volume as the actual flux. Because vehicle frame and equipment and the bodies of the astronauts create an extremely complex directional shield distribution about the emulsion pack, the actual flux incident upon the emulsion can be expected to show, especially for low energy particles, a similarly complex pattern with preferred and depleted directions; yet this inhomogeneity does not influence the determination of absorbed energy as long as the total track length is correctly known.

RESULTS

Figure 2 shows the integral energy spectrum for the proton flux recorded on mission Gemini 5 in the radiation pack on the left sternum of the command pilot. The dots indicate directly cumulative flux values obtained from the scanning scores. The smooth line represents the curve of best fit which was used for further data evaluation. As a first step, the integral spectrum was subjected to a point by point numerical differentiation leading to the differential spectrum shown in Figure 3. For the next step, the evaluation of the millirad dose, the assumption was made that the same track population as found in the scanned emulsion volume would have prevailed in a tissue sample of the same volume as the unprocessed emulsion. The validity of this proposition hinges on two prerequisites. Firstly, none of the recorded track segments must be of local origin in the emulsion. Secondly, the energy change along a track segment in the scanned volume must be small as compared to the absolute energy. The first requirement is fulfilled very satisfactorily. Tracks of local origin such as prongs from disintegration stars and neutron recoils were found to constitute, in the flown emulsions, a negligible percentage of the total track population.

Less reassuring is the situation concerning the second prerequisite. Consulting the range/energy function for protons in emulsion shown in Table I, one sees that a proton beam with an energy spectrum of the type shown in Figure 3 will undergo sizeable attenuation even in a few millimeters of emulsion if it enters the emulsion sheet at a grazing angle. The quantitative changes which this attenuation would

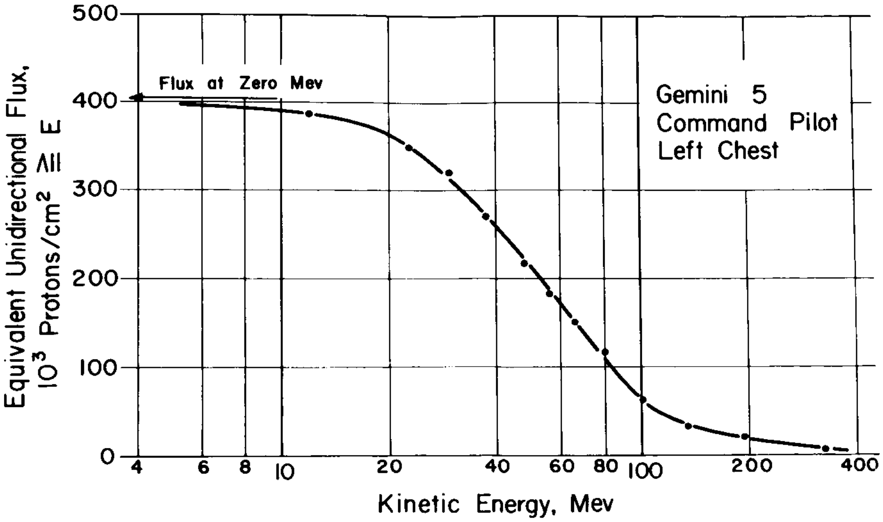

Figure 2

Integral Energy Spectrum of Proton Flux Recorded in Radiation Pack on Command Pilot's Left Sternum on Gemini 5

Dots indicate cumulative flux values directly obtained from the scanning scores. Smooth line was used for further evaluation. Data show total flux of mission.

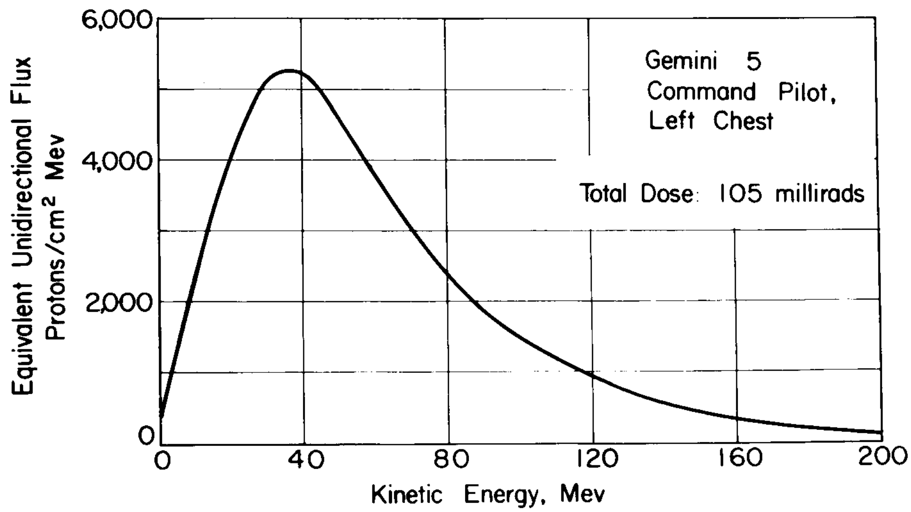

Figure 3

Differential Energy Spectrum of Proton Flux Recorded in Radiation Pack on Command Pilot's Left Sternum on Gemini 5

Spectrum was obtained by numerical differentiation of integral spectrum of Figure 2. Data show total flux of mission.

produce in a unidirectional beam are shown in Figure 4. The solid curve represents the differential energy spectrum actually recorded on mission Gemini 4 in the G.5/ K.2 pair of the pack in the command pilot's helmet. The two spectra drawn in broken lines show the original spectrum attenuated in two consecutive layers of 2000 micra emulsion each. The corresponding dose values are 48 millirads for the original spectrum and 40 and 35 millirads for the fictitious attenuated spectra. It should be emphasized that an attenuation as assumed in Figure 4 would occur only for unidirectional incidence at a grazing angle. The geometry in the actual exposure in orbit is greatly different, exhibiting a vastly more complicated pattern. Therefore, the local flux at spots 2000 micra apart in the flown emulsions cannot be expected to show the same degree of variation as the spectra in Figure 4. However, the differential flux in the energy

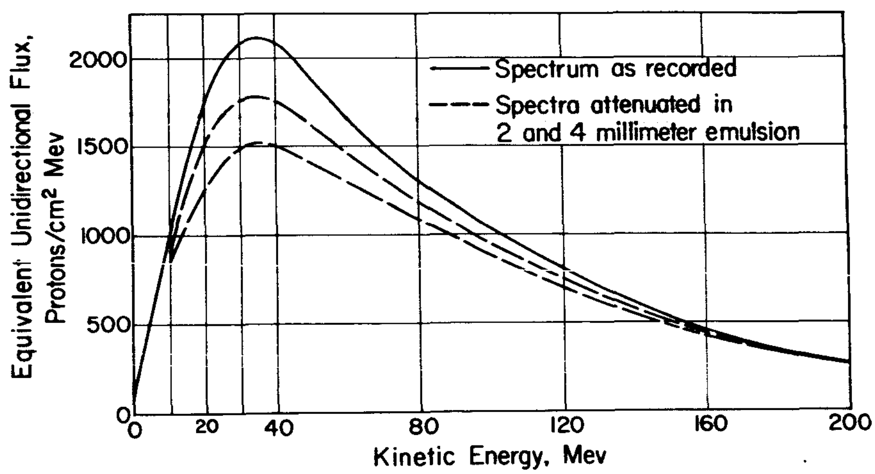

Figure 4

Differential Energy Spectrum of Proton Flux Recorded in Radiation Pack in Command Pilot's Helmet on Gemini 4

Solid Line: Spectrum as recorded
Broken Lines: Fictitious spectra as they would result from consecutive steps of attenuation in 2000 micra emulsion each

region from zero to a few Mev has been found to vary, at opposite edges of the same emulsion sheet, by a factor as high as 1.6. Data accumulated so far on variation of the enders count do not generally exhibit simple and systematic patterns in the flown emulsions. This finding seems to suggest that low energy protons were incident upon the emulsions not just from one narrow solid angle. Because of these apparently very complex distribution patterns, quantitative data on the directionality of the radiation incident upon the emulsion packs require a rather large scanning effort. Work in this direction is in progress.

A final question concerns the assessment of dose contributions from other nuclear components and from electrons and gamma rays. Heavy nuclei are present in the track population of the Gemini emulsions only in very small numbers. Most of the scans, by the time a statistically significant number of grain counted track segments had accumulated, did not even contain a single heavy track. Scanning for heavy tracks, therefore, was carried out as a separate procedure at lower magnification recording only black tracks. It should be pointed out that heavy nuclei of lower Z numbers produce grey tracks allowing grain counting. Such tracks have been treated, in the scanning procedures of the present investigation, like protons. That means they are contained in the energy spectra and their contribution to the total dose is correctly assessed. This seemed an acceptable proposition in view of their very small frequency and of the fact that in the context of this investigation only the total dose is of interest. Heavy tracks showing solid black cores that could not be grain counted were counted at low power magnification separately, as just mentioned. The Z numbers of these tracks were estimated by means of a comparison scale as described in Report 27. The combined result of all heavy counts in Gemini 4 emulsions leads to a dose of less than 2 millirads.

Exposure from gamma rays and electrons cannot be determined with nuclear emulsion with the same accuracy as the dose from nuclear particles. Aside from the fact that these ionizing agents do not produce dense straight tracks, they are the main constituents of the natural background ionization at sea level leading to an exposure that accrues at a rate of 0.5 to 0.8 millirad per 24 hours. Because of the lead times involved in preparing radiation packs for a mission, emulsions are usually about six weeks old when they are finally flown and processed. Theoretically, they have accumulated, during this time, some 20 millirads from background ionization. However, due to fading and other uncontrollable influences, the density of single grains and tortuous tracks and blobs from terminating electrons in the sea level controls differs markedly between individual emulsion sheets of the same batch. Therefore, merely estimates of exposure are possible by visual inspection under the microscope comparing the number of terminating electrons in a flown emulsion to that in the sea level control. On the basis of this comparison, it seems safe to say that the flight exposure from gamma rays and electrons is substantially smaller than the corresponding exposure from protons. Figures 5 and 6 show micrographs taken from a G.5 emulsion flown on Gemini 4 demonstrating the low level of single grains and tortuous tracks from terminating electrons.

CONCLUSIONS

The main significance of the results rests in the fact that the basic configuration of the energy spectrum of the proton exposure in the South Atlantic Anomaly, as it is found in Gemini type orbits, is now firmly established by direct measurements for all energies down to zero Mev. This is of importance especially for that part of the differential energy spectrum below the maximum where the flux drops steeply, since this section, because of the higher LET, contributes substantially to the total dose. As

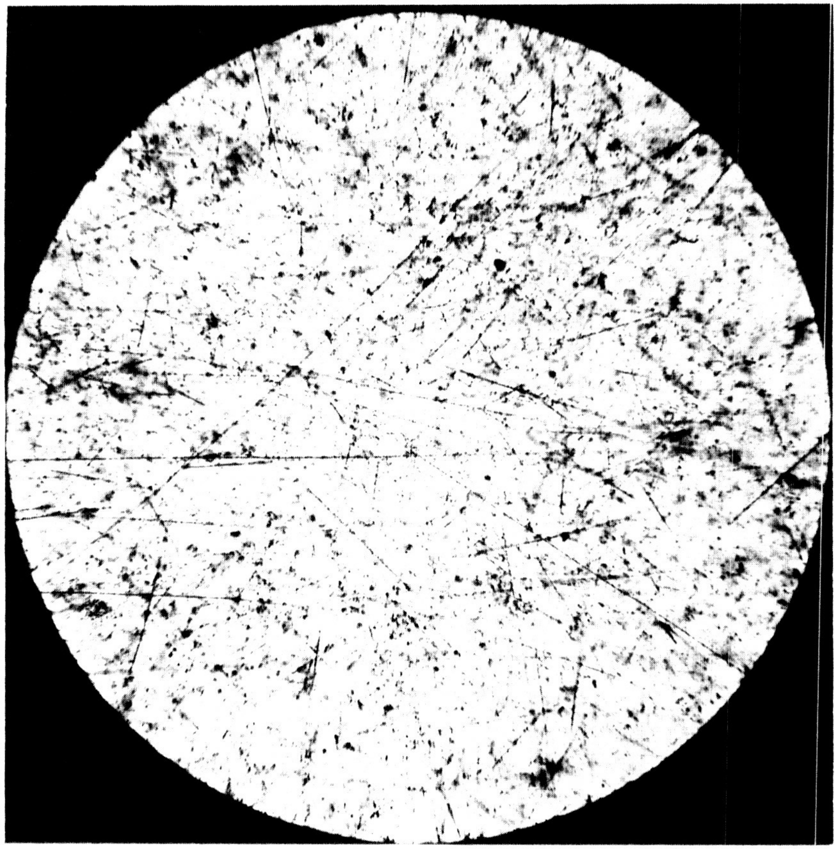

Figure 5

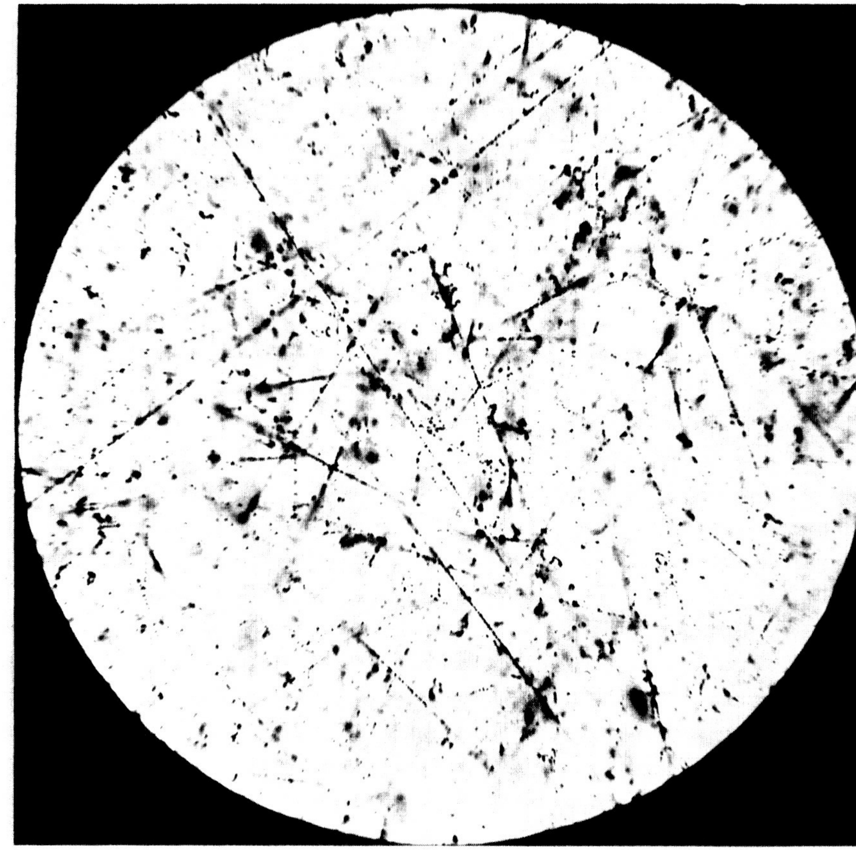

Figure 6

Micrographs of Ilford G.5 Emulsion in Radiation Pack on Left Sternum of Co-Pilot on Gemini 4 Taken at Different Magnifications (Left: 155X; Right: 315X)

Note low background of single grains and tortuous tracks from electrons.

a consequence of the large flux fraction in this low energy section, the energy spectrum is changed rapidly by any additional absorption to such an extent that within the same emulsion sheet the local dose can vary by as much as 20 per cent. A similarly steep drop of the depth dose distribution within the body is to be expected. These findings are in agreement with earlier theoretical studies (6, 7) which predicted a highly structured radiation field within the vehicle for energy spectra of the type found in the present investigation. They also agree well with the energy spectra for trapped protons as recorded by the Relay I satellite (8).

From a radiobiological viewpoint, the findings once again bring into sharp focus the predicament that for total body exposures in such highly structured radiation fields, few, if any, experimental data are available that would allow an accurate appraisal of the radiation injury. To be sure, a total body exposure of about 50 millirads as reported here for Gemini 4 and of 100 millirads for Gemini 5 do not yet pose any problems as far as the hazard to health for the astronauts is concerned. However, for exposures of longer duration in future space missions such as the Manned Orbital Laboratory, close assessments of the true exposure status of the crew will be necessary. The comfortably large safety margin, which rules and recommendations for terrestrial radiation safety practice provide, would not seem appropriate for space missions which call for a close and realistic balance of all risk factors involved.

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Security Classification

UNCLASSIFIED

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U.S. Naval Aerospace Medical Institute Pensacola, Florida	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE RADIATION MONITORING WITH NUCLEAR EMULSIONS ON PROJECT GEMINI. 1. EXPERIMENTAL DESIGN AND EVALUATION PROCEDURES: PARTIAL RESULTS ON MISSIONS 4 AND 5.

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (Last name, first name, initial)
Schaefer, Hermann J., and Sullivan, Jeremiah J.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
18 February 1966	12	8

8a. CONTRACT OR GRANT NO. b. PROJECT NO. MFO 22.02.02-5001 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NAMI-955 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) 33

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13. ABSTRACT

On Gemini 4 and 5, small packs of nuclear emulsions combined with other radiation sensors to flat pliable units were worn by the astronauts inside their space suits. Track and grain counting of 200 micra Ilford G.5 and K.2 emulsion pairs in the packs furnished the particle and energy spectrum of the radiation incident upon the astronaut's body. Evaluation of flux and energy spectrum in terms of millirad dose showed that the bulk of the exposure was due to trapped protons picked up in the South Atlantic Anomaly. The energy spectrum of the proton flux within the ship on the body of the astronaut is a continuum extending from zero to about 300 Mev, with a broad, well-developed maximum in the 30 to 40 Mev region. Because of the large fractional flux of low energy particles, the radiation level sensitively depends on local shield geometry producing variations of dose rate at different locations in the capsule of at least 60 per cent. Representative total doses were 48 millirads on Gemini 4 and 105 millirads on Gemini 5.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Radiation hazards in space Radiation exposure of astronauts on Gemini 4 and 5 Energy spectrum of trapped protons with Gemini vehicle Measurements of trapped protons with nuclear emulsion Radiation exposure in South Atlantic Anomaly						

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